THE APPLICATION OF REMOTE SENSING TO THE DEVELOPMENT AND FORMULATION OF HYDROLOGIC PLANNING MODELS

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EXECUTIVE SUMMARY

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PREFACE

The launch of LANDSAT has provided the water resource manager and practical hydrologist with broad prospects for efficient acquisition of data usable for hydrologic land use assessment, surface cover classification, physiographic analysis, surface water inventory, and for the extraction of information pertinent to soil properties. This information has value for constructing hydrologic planning models aimed at estimating peak outflow from rainfall inputs.

The reduction of satellite data to practical, operational information requires a clear, easily applicable methodology for converting these data into quantitative hydrologic parameters.

The fundamental objective of this effort is the development of such a methodology and its transfer to hydrologic users. It was realized that such technology transfer could be made far more effective by the parallel development and eventual demonstration of the results of a model, specifically structured to take full advantage of the capability of LANDSAT -- for example, its frequent recurrence and consequent ability to determine seasonal variations in the watershed's conditions. The category of Planning Models was chosen for development and demonstration because of the wide diffusion of such models down to capillary levels within the hierarchy of water resources users, and because their implementation is relatively simpler than real-time management

models, thus making optimum use of the resources available for this effort.

Consequently, the effort was structured along two major routes: the development of a hydrologic planning model specifically based upon remotely sensed inputs, including its test and verification from existing records; and the application of LANDSAT data to supplying the model's quantitative parameters and coefficients. Included was the investigation of the use of LANDSAT data as information inputs to all categories of hydrologic models requiring quantitative surface parameters for their effective functioning.

The effort thus far has consisted of two phases. The first focused on the definition of the "drivers" - those hydrologic processes to which peak runoff is most sensitive - and upon the synthesis of a simple yet effective model for the estimation of long-recurrence outflows. The results of the first phase effort were presented in the Final Report, "The Application of Remote Sensing to the Development and Formulation of Hydrologic Planning Models," dated January, 1975. The second phase has extended this work to include the development of a routing model for use in sensitivity analyses, and a quantitative investigation of the accuracy and completeness of the hydrologic information which can be extracted from remotely-sensed imagery.

This document reports the findings and conclusions of the Phase-two effort: it includes a summary of the results of the earlier work.

CHAPTER I

REVIEW OF THE FIRST PHASE EFFORT

Of critical concern to water resources planners and engineers is the ability to forecast peak flow events. The capability to estimate the magnitude and duration of large-recurrence outflows has a significant impact upon the accuracy of sizing and designing waterworks, and thus on their cost.

The tool available to the planner for these purposes is the hydrologic model. Although the inputs of different models vary, all require significant quantities of physiographic and hydrologic information; these data are typically expensive to obtain and are often only partially available. Remote sensing offers a new source of information which formerly had to be acquired by less efficient means or ignored altogether.

The first phase of this effort, conducted from February to December 1974, addressed four pertinent topics:

1) Identification of the "drivers" of peak flow events, i.e., the hydrologic phenomena (infiltration, antecedent soil moisture, etc.) to which the watershed's outflow is most sensitive.

2) The development of a model compatible to the maximum degree with remotely-sensed hydrologic inputs.

3) Verification of the model for actual watersheds.

4) Preliminary identification of the efficiency of remote sensing in determining the parameters of the model.

1.1) Investigation of Driver Phenomena

The investigation of the hydrologic drivers was accomplished by comparing the relative rates and magnitudes of hydrologic processes contributing to the runoff from long-recurrence events to ascertain which are important and which can be neglected without significant loss of accuracy.

Rain falling on a watershed is subject to several processes which abstract water and govern the flow. It was found that several processes can be omitted in the formulation of a peak rate model because of their limited impact. Except for very special circumstances, peak flow can be adequately modelled by considering only precipitation, infiltration and surface flow - both overland and in the channel.

The set of the principal drivers of planning models can thus be defined as shown in Table 1, which also indicates that several of the drivers are remotely measurable or inferrable.

1.2) Development of Remote Sensing Model

The following criteria were followed in the structuring of a peak-rate model:

1) The model would be modular, to allow the user flexibility of application.

TABLE 1

PLANNING MODEL COMPONENTS

PROCESSES	DRIVERS	REMOTE SENSING POTENTIAL
Overland Flow	Slope	*
	Surface Friction	*
	Drainage Density & Pattern	*
Infiltration	Soil Permeabilities	
	Soil Moisture Capacity	
	Antecedent Soil Moisture	*
Rainfall	Regional & Seasonal	
	Recurrence Statistics	

2) The model would provide the long-recurrence peak outflow rate; development of a model to yield the hydrograph was reserved for a later phase of the effort.

The peak rate model was constructed from the following modules:

Rain Recurrence Module: an empirical formulation used to calculate the expected magnitude of large recurrence rainfalls.

Rainfall Spatial Correction Module: the introduction of a factor to convert point rainfall to its areal equivalent for large basins.

Sub-surface Abstractions (Infiltration) Module: the Holtan infiltration equation, relating infiltration rate to maturity of cover, average vegetative cover, and soil moisture capacity.

Overland Flow Module: a formulation which relates maximum overland flow rate to watershed slope, area, surface friction, channel length and rainfall input.

$$Q = 2L\bar{l}\ \xi \left[\frac{\phi\ (\bar{l}\bar{n})^{\frac{3}{5}}}{\xi^{\frac{2}{5}}\ s^{\frac{3}{10}}\ (3600)} \right]^{\frac{1}{0.4 - \frac{1}{\alpha_3}}}$$

where: Q = maximum outflow rate, $m^3/sec/km^2$

L = channel length, m

$\bar{l}$ = length of average strip, m

$\bar{n}$ = average Manning's "n"

ϕ = routing factor

$\xi = K\ \alpha_1\ T^{\alpha_2}$

K = infiltration and spatial correction factor

T = rain recurrence interval, years

s = average slope, m/m

α_1, α_2, α_3 = constants, function of location

1.3) Verification of the Model

Validation of the model required testing against a set of real watersheds possessing long-term records and representing a variety of envirormental conditions. Such a set has been developed by the U.S. Department of Agriculture, Agricultural Research Service (ARS). From this set of approximately 250 watersheds, the basins with area greater than 40 hectares were selected to form the analytic sample.

Initial verification of the model was made on a subset of nine basins selected for geographic and hydrologic diversity. The computed flow rate and the rate statistically derived from the measurement records were compared. Computation of peak flow was also made using other models in common usage - the Rational Formula, the S.C.S. model, and Cook's equation - for the same watershed sample.

The peak-rate model yielded estimates within ±15% of those derived from runoff records for seven of the nine test watersheds. The results for two watersheds exceeded this accuracy bound. It appeared that these large errors might be attributable to the "complexity" of the two basins, both of which are composed of numerous sub-basins of diverse characteristics hence requiring more complex routing than incorporated in the model. The development of the routing module will be described in Chapter III.

1.4) Identification of the Role of Remote Sensing in Hydrologic Modelling

A visual analysis was performed of one watershed, at Chickasha, Oklahoma, from black and white, Band 5, LANDSAT imagery. The findings

of this analysis showed that substantial hydrologic information can be measured from low resolution, single-band, black and white imagery. The parameters identified and measured were: surface water bodies, Land Use Type 2 and 3 surface cover classes, channel length, and watershed area.

1.5) Conclusions from the First Phase Effort

1. A model for the prediction of peak flow events was structured, specifically designed to take maximum advantage of the data and information stream available from remote sensing.

2. The predictions of the model in its simplified version were tested against:

    a. The predictions from three of the most employed contemporary planning models -- i.e., the Rational Formula method, Cook's method, and the Soil Conservation Service method; and,

    b. The statistical recurrence analysis of the streamgage records of the nine test watersheds.

3. The results indicate that, within the range of applicability of its simplified version, the model appears to be an improvement over conventional hydrologic planning models.

4. The techniques for extracting the model inputs and parameters from remotely sensed information were investigated.

Their feasibility was identified by visual analysis of LANDSAT imagery for the ARS watershed at Chickasha, Oklahoma.

CHAPTER II

APPROACH TO THE PHASE 2 EFFORT

The Phase 2 effort concentrated in two areas:

1) The improvement and extended verification of the planning model, including routing.

2) The analysis of LANDSAT imagery to determine practical procedures for the extraction of quantitative hydrologic information usable in Planning Models.

The first area included four tasks: a) the extension of the peak-rate model to a larger, statistically significant watershed sample; b) the analysis of the time-profile of the critical rainfall and of the regional and seasonal characteristics of peak flow to determine what is the "planning rain," i.e., the rainfall which defines the critical outflow; c) the sensitivity of overland flow to changes of physical basin parameters; and, d) the synthesis of a routing model based on remotely-sensed inputs.

The second area consisted of three tasks: a) investigation of techniques for extraction of hydrologic data; b) investigation to determine the information content of each MSS band and multi-band combinations; and, c) in-depth quantitative analysis of a specific watershed from LANDSAT data.

CHAPTER III

EXPANDED VERIFICATION OF PEAK-RATE MODEL AND DEVELOPMENT OF ROUTING MODEL

3.1) Expanded Verification of Peak-Rate Model

A total of thirty-one basins satisfying the criteria of "simplicity" were selected in this effort. These watersheds ranged in area from 40 to about 2000 hectares. The parameters required were computed for each watershed, and the peak rate model was run for each of the 31 simple watersheds, as were the S.C.S. formula, Cook's model and the Rational formula. Mean errors for the peak rate model were about 56% compared with 62.5%, 99.2%, and 80.3%, for the S.C.S., Cook, and Rational models, respectively. Statistical tests run on the errors indicated that an improvement had been realized.

Development of the peak rate model made apparent some other potential sources of forecast errors. To improve prediction accuracy of the routing model, several questions needed to be answered:

1) What is the "planning rain," i.e. what rainfall input corresponds to the peak flow output and what are its temporal and areal distributions?

2) What seasonal and geographic factors are pertinent? Do rainfall and runoff exhibit propensities to occur during particular seasons in particular locations? What seasonally variant conditions should be included in the model?

3) What is the quantitative sensitivity of basin runoff to variations in surface parameters? How accurately, then, does one

need to measure slope, friction factors, etc. to obviate the introduction of unacceptable errors.

4) How should the appropriate basin sub-area be selected? Since values for each micro element of the basin are costly to measure in practice, how should the hydrologic parameters be combined into an average value yielding correct results?

The following describes each question and presents the solution derived.

In general, no single type of rain event causes the peak basin outflow. A fifty-year recurrence runoff, for example, can be produced by one intense rainfall or by a series of lesser events. This fact, already indicated by various researchers, was verified for the watershed test sample by examing the relation between large-recurrence rainfalls and runoffs. This required the analysis of detailed records of rainfall and runoff rates and masses at time intervals of a few minutes in several watersheds, to identify the largest runoff events, the corresponding hydrographs, and hyetographs of the generating rainfall(s). No easily-discernible relation appeared to exist between the runoff and the rainfall of equal recurrence. The conclusion which was reached is that runoff is sensitive to several factors, among which rainfall rate is only one. Since no direct connection could be established, further analyses were performed to estimate the temporal profile, duration, and magnitude of the planning rain.

A computer model developed by D.E. Overton was used to determine the temporal profile of the planning rain. The model simulates the runoff resultant from a given rainfall input for a unit width "strip" of

any length. Several rainfalls of equal volume but with different temporal profiles were simulated and the resultant runoff hydrographs recorded. A significant increase in outflow was apparent from rains of triangular shape. Rainfall records from the test watersheds showed also that the large recurrence rain profiles tend to be triangularly shaped. It thus appears that the triangular profile should be used for the planning rain.

As regards the sensitivity of runoff to timing of the rainfall peak, it was discovered that the discharge peak varies as the time of peak rain, rising to a maximum and then falling off. The computer model showed it valid to assume that the planning rain should have its maximum occur near the midpoint of its duration.

The appropriate duration was estimated as well. The strip model demonstrated that the highest runoff rate which can be expected from a rainfall of fixed volume will occur at the time of concentration. The rainfall, then, must be at least of duration t_c to ensure that the watershed has reached its ultimate outflow rate. Finally, the recurrence interval of the rain was determined. The rates of peak rainfalls were plotted against their recurrence intervals for the nine watershed test sample. The results showed that for intervals greater than about fifty years, the increase of rainfall rate was small. The fifty year recurrence was therefore selected. The planning rain, then, should be one of triangular shape, duration of t_c, and of fifty-year recurrence.

Hydrologic planning models will be most accurate if they mirror the conditions extant in the basin during the season when the peaks are most likely to occur. It is therefore important to ascertain whether runoff peaks exhibit seasonal regularities and to identify the critical seasons for the watershed under study.

A geographically diverse sample of watersheds was selected for this analysis, comprising 15 ARS basins with records longer than 15 years. The annual peak discharge for each basin by year and month of occurrence was recorded, and a chart prepared showing the probability that an annual peak would happen in any given month. The analysis permits the tentative conclusion that in the regions where peak events are dominated by surface parameters, (Danville, Blacksburg) the distribution is bimodal, i.e. flood peaks tend to occur in two distinct periods of the year, typically late spring and late summer. Watersheds in transition regions (Coshocton, Waco) exhibit a less marked seasonal tendency. The probability of occurrence of peak flows is more equally spread over a six to nine month interval. Those basins which are heavily sub-surface dominant (Safford, Albuquerque) show single-mode distributions. Nearly all their peak flows occur within a three month period in late summer.

An analysis of sensitivity of runoff to surface parameters was performed for two purposes:

1) to determine how accurately surface characteristics must be measured for input to models, i.e., what are acceptable errors in estimation of values of hydrologic parameters.

2) to develop a rationale for "averaging" surface parameters - for summing the values for each point on the watershed into some computationally manageable sub-area.

Computer runs were therefore made to assess the sensitivity of discharge to the surface parameter of slope and surface friction.

To date, computer analysis has been conducted for a basin strip of average dimensions and for a typical rainfall input. The principal findings were:

a) Duration of runoff peak is most sensitive to slope at values less than about 10%. When slopes of watersheds are greater than 10%, an average value can be approximated. In flat basins, though, more detailed ground truth should be consulted. The same sensitivity applies to estimates of time of concentration - the critical region consists of the lower slopes.

b) Irregular watershed slopes can be approximated by straight planes where slope variations are less than about 5%; otherwise, each strip should be divided with the outflow of the uppermost becoming the input to the lower.

c) The runoff peak rate is most sensitive to surface friction in basins with lower resistivities ($n < 0.04$), while the duration of the peak is most sensitive to higher frictions. It follows that a remotely-sensed estimate of surface cover needs to be adequate enough to separate it into classes

with similar values of Manning's "n". It is patent then that a remote sensor should be able to separate forests from fields, fields from soil, and soil from urban areas, for example.

3.2) Development of Routing Module

In large watersheds, or in those composed of several tributary streams, the assumption that all areas of the basin contribute to the outflow hydrograph simultaneously leads to errors. The hydrograph of each sub-watershed can differ from those of its neighbors in temporal distribution, magnitude and duration. The overall outflow from the basin is the combination of these hydrographs, appropriately added to account for the time lag required for runoff from each to reach the basin outlet.

Complex watersheds typically contain more than one predominant channel. The outflow from each sub-area does not drain directly into the main channel; rather, some flows first to secondary streams. The contribution of certain sub-areas is delayed. An effective hydrologic model accomplishes this mathematically; it computes the hydrograph of each sub-watershed and sums them according to a time-delay (routing) function.

The approach to developing the routing module of the peak-rate model was to approximate a watershed by a series of unit strips and then to sum the hydrographs according to a time delay function. The model, therefore, consists of an overland flow component (unit strips) and a channel flow component (lag time function). In line with the intent

of this effort, the model was designed to keep the computing hardware to a minimum. The model has successfully been applied to sensitivity analysis of basin shape and areal distribution of rainfall. It offers amenability to variable precipitation inputs and surface conditions, and, additionally affords ample opportunities for use of remote sensing inputs.

CHAPTER IV

HYDROLOGIC ANALYSIS OF LANDSAT IMAGERY

This task included three principal components:

1) Analysis of the state of the art of techniques for measuring surface characteristics of hydrologic significance and of their cost, implementation time, equipment and skill requirements.

2) Evaluation of the specific hydrologic information content of the four LANDSAT bands and determination of which bands or combination of bands are best suited to measuring each model input.

3) Quantitative hydrologic analysis of a complete watershed using LANDSAT imagery and available ground truth.

4.1) Analysis of the State of the Art of Measurement of Hydrologic Parameters from Remotely-Sensed Data

This investigation focused upon measurement methods for those remotely sensible hydrologic factors of most immediate value to watershed modelling:

1) Physiographic Basin Measurement

2) Surface Cover Identification & Classification

3) Soils Classification

It was determined that physiographic data - watershed area, overland flow length, drainage density, and channel dimensions - could be extracted from LANDSAT imagery to an accuracy comparable to other

commonly - available sources of ground truth. Surface cover could be classified by relatively simple visual means into categories detailed enough for assigning quantitative coefficients. Soils classification typically relies upon inference from surface cover and is, therefore, greatly facilitated by the use of ancillary ground truth.

4.2) Analysis of Hydrologic Information Content of LANDSAT Bands

The objective of this task was to determine the extent to which information directly applicable to hydrologic models can be gleaned from the satellite data. To accomplish this function, an image viewing system was assembled, capable of projecting single or multiband LANDSAT imagery onto a work surface.

Two of the ARS experimental watersheds were selected for visual photointerpretation of LANDSAT images. Those chosen - the Thorne Creek basin near Blacksburg, Virginia, and Watershed W-10 near Oxford, Mississippi - were singled out due to the availability of adequate ground truth in the form of topographic maps, soil surveys and aerial photography. It was found that information sufficient to determine hydrologic coefficients for these basins from LANDSAT data using relatively uncomplicated visual techniques. Particularly, an estimation of forest area was made for the Oxford watershed, for individual bands and certain two-band combinations. The results (Table 1) show that accuracies sufficient for modelling can be attained when measurements are made from the most appropriate MSS Band.

TABLE 1

FOREST/VEGETATIVE AREA COMPARISON

	Band 7	Band 5	Intersection 5 & 7	Union 5 & 7
Total Area Measured	1730 Ha.	1309 Ha.	1123 Ha.	1911 Ha.
Omission Error	6.1% (81 Ha.)	9.3% (123 Ha.)	2.8% (37 Ha.)	2.1% (28 Ha.)
Commission Error	31.1% (411 Ha.)	21.2% (281 Ha.)	18.9% (250 Ha.)	38.3% (506 Ha.)
Inventory Mode Error	31%	1.01%	15.1%	44.5%

Actual area = 1296 Ha. (from U.S.G.S. 1:24,000 Scale Topographic Map)

The following conclusions could be made regarding the relative value of each band, limited, of course, to the examples analyzed:

1) Band 7 appears to be best for identification and measurement of surface water area. This is because of the very low reflectance of standing water in the 0.8-1.1μm range and consequent high contrast with its surroundings. Though no significant urbanization exists in either basin, analysis of the remainder of the LANDSAT scene showed Band 7 to be good also for identification of urban land use.

2) Band 5 offers much more information about vegetation than the other bands. Where vegetative cover typically appears only as one or two shades of gray in other bands, Band 5 often yields twice that number.

3) The information derivable from Band 6 is correlated with that of Band 7; likewise, Band 4 is correlated with Band 5. In both cases, the detail in the former has proven inferior. Band 4, however, was found useful in the measurement of road-courses.

4.3) Quantitative Hydrologic Analysis of LANDSAT Imagery

The results of the preliminary visual analysis of the Blacksburg and Oxford watersheds were sufficiently promising as to warrant its extension to a detailed study of a third basin, possessing high-quality recent ground truth. The objective was to determine how many surface features could be identified and measured; to assess the accuracies achievable in the inventory and land use modes. The Muddy Branch Creek in Montgomery County, Maryland, was selected for study. The potential for multiband analysis identified earlier was tested.

It was determined that single bands contain useful but different data and hypothesized that a composite image would optimize the information value. This hypothesis was confirmed through in-depth analysis of the Muddy Branch basin. The results showed that five categories of surface cover - forests, fields, lakes, bare soil, and urban areas - could be distinguished. Surface features of the watershed were identified, measured, and checked against aerial photographs ground truth. The inventory mode errors, those of most concern to the modeller, are given in Table 2. It is clear that estimation errors have been much improved over those derived from single band analysis. The results showed inventory errors to be well within acceptable limits for modelling and useful for direct computation of model parameters.

TABLE 2

INVENTORY MODE

	AREA LANDSAT	% OF WATERSHED	AREA AERIAL	% OF WATERSHED	INVENTORY ERROR
Urban	1,376 acres	11	1,604 acres	12	-14%
Forest	3,068 acres	24	3,192 acres	23	- 4%
Lakes	74 acres	1	72 acres	1	+ 3%
Soil	1,420 acres	11	1,352 acres	10	+ 5%
Fields	7,044 acres	54	7,480 acres	55	+ 6%

The multi-band color composites used in the analysis greatly improved the separability of land use categories over single-band imagery. Quantitative hydrologic coefficients could be assigned with accuracies commensurate with those made from the ground truth.

CHAPTER V

SUMMARY OF FINDINGS AND CONCLUSIONS

Three tasks were undertaken in this effort: 1) the validation of the peak-rate model on an expanded set of watersheds; 2) the development of a routing model for complex basins; and, 3) the quantitative hydrologic analysis of LANDSAT imagery. The findings and results are described in the following.

5.1) Expanded Validation of the Peak-Rate Model

A thirty-one watershed sample was selected with significant geographic and hydrologic diversity. The prediction supplied by the model was tested for each, with this output compared to the records and to forecasts computed by using three other conventional planning models. The remote sensing model gave improved variability and accuracies commensurate to the other three models. Mean errors for the peak rate model were 56% as compared with 62.5%, 99.2% and 80.3% for the SCS, Cook and Rational models, respectively. The remote-sensing model in its current implementation applies to "simple" basins - composed of a single predominant channel, and devoid of significant sub-basins.

Additionally, some potential sources of modelling error were identified and therefore a number of pertinent questions were addressed. First, the "planning rain" had to be defined. Subsequent analyses led to the conclusion that this rain could be best approximated by one of triangular shape, having a duration approximately equal to the time of concentration of the basin and having a recurrence of approximately fifty-

years. Second, seasonal characteristics of peak flow phenomena were investigated to ascertain what impacts they might have on a model.

It was discovered that different geographic regions exhibit varying seasonal properties, but that, within a region the characteristics are similar. Those basins located in subsurface-dominated areas, for example, show a propensity to produce peak discharge in a two to three month period in late summer hence requiring increased satellite coverage during this period. The model, therefore, should measure the physiographic (drainage density) and hydrologic (surface cover, soil moisture, etc.) characteristics which exist in the critical season. Finally, sensitivities of surface parameters were examined. It was shown that the runoff rates were sensitive to slope primarily at low slopes. Further, it was found that sensitivity to surface function requires that a remote sensor be able to classify surface cover into categories with similar values of Manning's "n".

5.2) Development of a Routing Model

The need for a model to treat "complex" basins was identified above. A model was developed which approximates the watershed by a series of strips, each having its own set of surface and rainfall parameters. The output of these strips is summed using a simple time delay function which accounts for the length of overland flow and the hydrologic characteristics of the channel. The complete model was applied to analysis of the sensitivity of runoff to basin slope and areal extent of rainfall. It was discovered that both are significant and should be provided for by the planning model. The routing model met these cri-

teria and also those of high remote sensing input potential and computational simplicity.

5.3) Hydrologic Analysis of LANDSAT imagery

The final task was aimed at using remote sensing directly to determine hydrologic information content of the LANDSAT bands and to attempt to simply extract the necessary hydrologic data. It was found that information sufficient to determine several of the important inputs to the model could be determined from LANDSAT data using relatively uncomplicated visual techniques. Moreover, it was determined that single bands contain useful but different data and hypothesized that a composite image would optimize the information value. This hypothesis was confirmed through analysis of the Muddy Branch basin. Surface features of the watershed were identified, measured, and checked against aerial photographs ground truth. The results showed inventory errors to be well within acceptable limits for modelling and useful for direct computation of model parameters.